Ocean Engineering 145 (2017) 277–289

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Review of ship safety domains: Models and applications

Rafal Szlapczynski [a], Joanna Szlapczynska [b,*]

[a] Faculty of Ocean Engineering and Ship Technology, Gdansk University of Technology, Poland
[b] Faculty of Navigation, Gdynia Maritime University, Poland

ARTICLE INFO

Keywords:
Ship domain
Collision avoidance
Collision risk
Maritime traffic engineering

ABSTRACT

Ship safety domain is a term which is widely used in research on collision avoidance and traffic engineering among others. Classic ship domains have been compared in multiple reports. However, up till now there has been no work summing up contemporary research in this field. The paper offers a systematic and critical review of the newer ship domain models and related research. It discusses multiple differences in approach to ship domain concept: from definitions and safety criteria, through research methodologies and factors taken into account, to sometimes largely different results obtained by various authors. The paper also points out some interpretation ambiguities related to ship domain and sums up present trends of its development and applications.

1. Introduction

Ship safety domain is a generalization of a safe distance and its introduction to maritime navigation comes from the observation that the safe distance is not the same in all directions. The term "ship domain" is widely used, but often with different meanings, depending on a particular author's definition or a purpose for developing domain's model. This may lead to confusion, especially if such domains are compared in terms of size and shape.

Papers on ship domains are numerous and their authors provide brief syntheses of what has already been done in the field. Summaries of ship domain-related research have also been included in papers reviewing collision avoidance methods (Tam et al., 2009). However, until now there has been no wider publication fully devoted to reviewing contemporary ship domain models and related research. The current paper aims to fill this gap by offering a critical ship domains summary.

Ship domains can be roughly divided into those developed by theoretical analyses, those based on experts' knowledge and those determined empirically, though it must be said that the three groups are not mutually exclusive and combinations of various methods are sometimes used, e.g. (Dinh and Im, 2016). Domain models determined empirically are usually simpler, since empirical data make it hard to isolate the impact of multiple parameters. Because of this simplicity, potential applications of these models are limited to problems, where sizes and general shapes of domains are enough to work on the statistical level and precise dimensions are less important. Therefore, empirical domains are successfully used for determining capacity of local waterways, but usually are not detailed enough for ship-ship collision avoidance. As for knowledge-based and analysis-based models, their application scope is much wider and extends from abovementioned collision avoidance to detection of near miss situations and waterway risk analysis. As these purposes are much more demanding, the domains are heavily parameterised to cover multiple elements contributing to collision risk.

What is common for all models is that they are affected by water regions, though to a varying degree. In case of determining capacity or waterway risk it is a particular water region that is of interest, mostly because of its shape, traffic density and traffic patterns. In case of collision avoidance systems it is rather a type of the water region: narrow waterways, restricted (but considerably wider) waters or open waters.

The methods of determining ship domains have evolved with time. Early models have usually been based on statistically processed radar data (Fuji and Tanaka, 1971; Goodwin, 1975; Coldwell, 1983). This empirical approach is still continued, but AIS has replaced radar as a data source and more advanced statistical methods are applied to data processing (Hansen et al., 2013; van Iperen, 2015). Utilising expert navigators' knowledge (Pietrzykowski and Uriasz, 2009), analytical approach (Wang et al., 2010; Wang, 2013) or a combination of both (Dinh and Im, 2016) is preferred when collision avoidance systems, near miss detection or collision risk analysis are concerned.

The rest of the paper is organised as follows. Domain's classic definitions are presented and analysed in Section 2, followed by a discussion of why, how and with what results domains have been determined by various contemporary researchers (Section 3). Section 4 presents their applications and Section 5 related research methods and measures

* Corresponding author.
E-mail address: asiasz@am.gdynia.pl (J. Szlapczynska).

http://dx.doi.org/10.1016/j.oceaneng.2017.09.020
Received 13 January 2017; Received in revised form 16 August 2017; Accepted 13 September 2017
Available online 22 September 2017
0029-8018/© 2017 Elsevier Ltd. All rights reserved.

alternative to ship domains. Finally, the conclusions, including unsolved problems and predicted future of ship domains, are presented in Section 6.

2. Domains definitions, interpretations and their practical implications

While all of the researchers determine or propose dimensions of their respective ship domain models, it must be noted here that these dimensions may result in different spacing between ships, depending on the definition of a ship domain and the associated safety criteria. Therefore, three classic definitions are recalled here and their interpretations and implications are discussed later in this section.

The term of a ship domain was first introduced in (Fuji, 1971), where the effective domain was defined as: '*a two-dimensional area surrounding a ship which other ships must avoid – it may be considered as the area of evasion*'. The dimensions of the effective domain boundary were there defined as the distance from the central ship at which the density of other ships reaches a local maximum.

Similar definitions can be found in two successive works. According to Goodwin (1975) the domain is '*the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary obstacles*'. In (Coldwell, 1983) it is '*the effective area around a ship which a typical navigator actually keeps free with respect to other ships*'. The obvious difference is that in the latter definition the results rather than preferences are accentuated.

In general, the above definitions are close to each other, yet are interpreted in multiple ways by various authors, leading to various safety criteria applied in their research. In practice, using a ship domain in an encounter situation may be combined with one of the following four safety criteria, as presented in Fig. 1:

a) own ship's (OS) domain should not be violated by a target ship (TS),
b) a target ship's (TS) domain should not be violated by the own ship (OS),
c) neither of the ship domains should be violated (a conjunction of the first two conditions),
d) ship domains should not overlap - their areas should remain mutually exclusive (the effective spacing will be a sum of spacing resulting from each domain).

Each of these criteria is represented by some researchers. Fuji's definition implies that a give way ship should try not to violate the domain of a stand-on one, while according to Coldwell a navigator takes care of his own domain rather than that of a target. As for Goodwin, the term of "central ship" used in the paper does not imply explicitly whether a ship should avoid violating its own domain or that of a target. However, it might be argued that if the definitions concern every navigator than neither domain should be violated during an encounter of two ships, which supports the third of the listed criteria. The fourth one (domains not overlapping) has been lately used in (Rawson et al., 2014; Wang and Chin, 2016).

The practical differences between those four criteria are essential and will be analysed in detail further in the text. In general, their impact is equally important as the size and shape of a domain, since it largely affects effective spacing between ships.

The first two criteria may be considered asymmetric – even if the same domain is used, they may lead to different estimations of safety, depending on which ship does the assessment. The other two are symmetric – as long as the same domain is applied, the assessment of the situation would be the same regardless of the point of view. Of these four criteria the last one is by far the strongest and it must be stated clearly here that it is not compliant with any domain's definitions given above. According to these definitions the domain is the area that stays or should stay clear of other vessels, not of other vessel's domains (the latter would mean a recursive definition and would be unintuitive for a navigator). Unfortunately, all of the four criteria, including the last one, are used by researchers, who then compare their domain dimensions with other domains, which is meaningless in case of different criteria. Depending on which of the four criteria listed above is to be applied, different minimum spacing will be kept, even if the same domain model is used. In practice the differences in spacing due to applying different criteria will be comparable and sometimes even substantially larger than the differences in domain dimensions according to different authors. The details are provided below.

To make the analysis easier to follow, let us assume a ship domain's shape and size according to Coldwell, whose dimensions (multiplies of a ship length given as *L*) are given in Fig. 2. Coldwell specified different dimension values for meeting (head-on and crossing) and overtaking encounters (Fig. 2). Since his "meeting" domain does not have the aft sector (which is understandable in case of a head-on encounter, but problematic for a crossing), the "meeting" domain has been adjusted for the experiment in accordance with the general trend identified by most researchers (the aft sector smaller than the fore sector), as shown in Fig. 3.

Thus, the domain dimensions are as follows.

– For overtaking encounters: semi-major axis - 6 L, semi-minor axis – 1.75 L.
– For head-on and crossing encounters: semi-major axis – 5 L, semi-minor axis – 2.5 L.

Additionally, for head-on and crossing encounters the ship is moved from the ellipse's centre towards port by 0.75 L and towards aft by 1.1 L, with the resulting safe distances for respective sectors being:

– fore sector – 6.1 L,
– aft sector – 3.9 L,

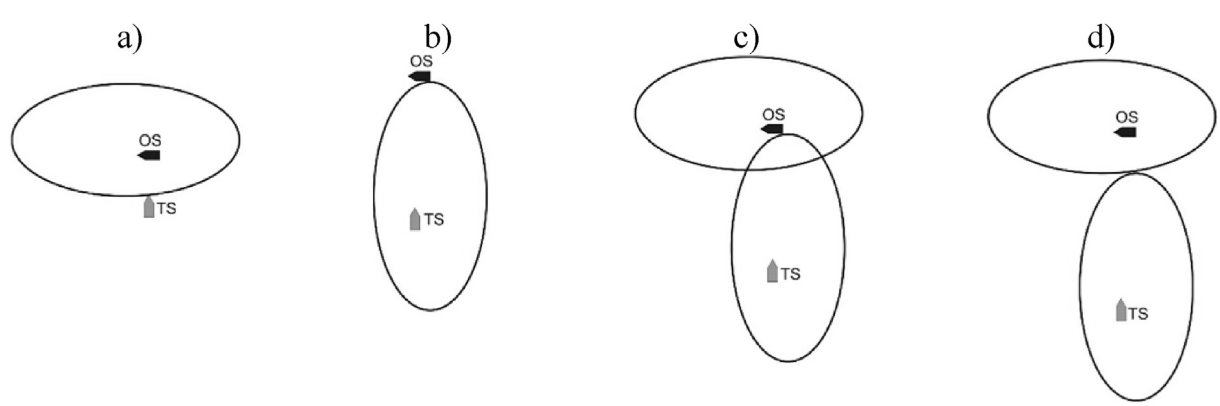

Fig. 1. Different domain-based safety criteria: a) OS domain is not violated, b) TS domain is not violated, c) neither OS nor TS domain is violated, d) domains do not overlap.

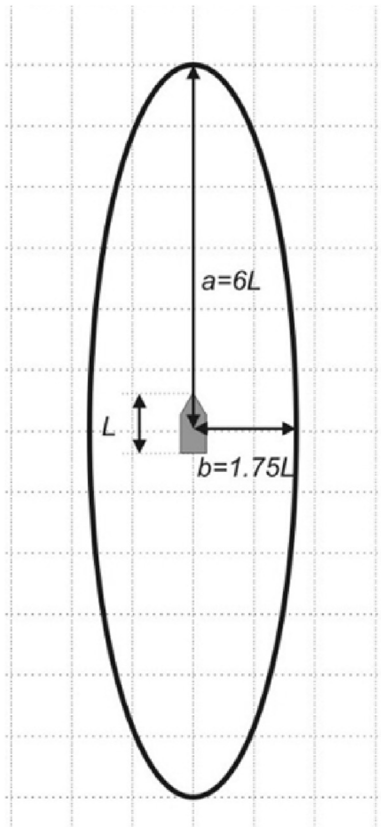

Fig. 2. Coldwell's domain for overtaking.

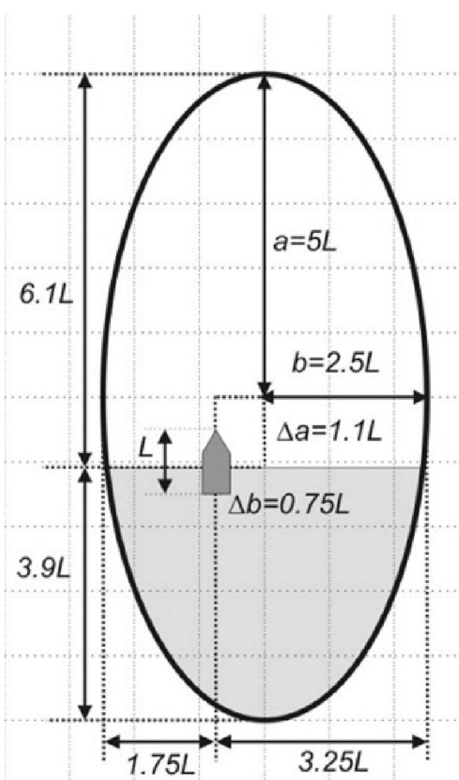

Fig. 3. Coldwell's domain for head-on and crossing with an additional aft sector in grey.

– port sector – 1.75 L,
– starboard sector – 3.25 L.

To emphasize differences in results it has been assumed that the ships dimensions are:

– Own ship: length, $L_1 = 160$ m; beam $B_1 = 20$ m.
– Target: length, $L_2 = 320$ m; beam, $B_2 = 40$ m.

The values of minimum spacing for the four criteria and seven types of encounters are given in Table 1 and Table 2. Three selected encounter situations from Table 1 have been illustrated in Fig. 4, Fig. 5 and Fig. 6, whose a–d parts correspond to different domain approaches (Fig. 1a–d).

The presented results yield the following conclusions:

1. Applying the first criterion (Fig. 1a) results in a relatively small spacing for crossing astern or ahead of a target. In case of a target on starboard (a stand-on one) the separation is larger when crossing ahead and thus compliant with COLREGS (IMO, 1972; Cockcroft and Lameijer, 2011). Unfortunately, it is the other way round in case of a target on port (e.g. Figure 5a): the extremely small separation in case of crossing ahead of a give-way target is problematic. If the give-way target does not manoeuvre, the own ship should probably initiate an escape action rather than accept such a small spacing.
2. The second criterion works similarly to the first one, but gives a much larger separation in case of crossing ahead of a target. However, it must be noted that if it is the target that crosses ahead of the own ship, this criterion will give the same assessment as the first one in case of the own ship crossing ahead of a target.
3. The third criterion results in a reasonable spacing for all of the illustrated encounters.
4. The last criterion obviously results in a large spacing between ships, since the spacing here is a sum of two single separating areas.
5. For the first two criteria the expected minimum spacing is different from the point of view of both ships (especially in case of crossing), which may contribute to a different assessment of the same situation by them. This issue has been already raised by Zhao et al. (1993), who analysed a head-on encounter of two ships with asymmetrical domains. Of course, in practice, assessments made from two ships would always slightly differ, but here they will differ substantially by definition, which should not take place.

Taken into account all of the above it might be concluded that the third safety criterion (Figure 1c, Figs. 4 and 6c) is the only one that is both safe and fully complaint with the domain's classic definitions. However, it must be emphasized, that the above analysis concerns situations governed by Rules 13 to 16 of COLREGS. Additional rules may apply within harbour areas (region-specific regulations and Rule 10 of COLREGS concerning Traffic Separation Schemes) or for narrow channels (Rule 9 of COLREGS), which is taken into account in some ship domain-related research (Pietrzykowski 2008, Rawson et al. 2014, Wang and Chin, 2016).

3. Methods, factors taken into account and major findings

A summary of safety criteria applied by various authors and methods of determining ship domains is given in Table 3. In two cases safety criteria are not specified in Table 3 ('N/A' entries): they were not mentioned explicitly by an author in (Goodwin, 1975) and were irrelevant for the project by (Hansen et al., 2013), which did not address collision avoidance problem. As for the methods of determining ship domains, they can be divided into three groups: empirical, knowledge-based and safety analysis-based. Domains representing those three approaches have been presented in sections 3.1–3.3, though it must be mentioned that these three groups are not mutually exclusive and combinations of two or three approaches are possible.

Table 1
Approximated minimum spacing for Coldwell's domain if own ship's length and beam are: L_1, B_1 and target's length and beam are L_2, B_2, respectively.

Encounter/Safety condition	Own domain not violated	Target's domain not violated	Neither domain is violated	Domains not overlapping
Head-on (port to a target)	$1.75L_1$-$0.5B_1$	$1.75L_2$-$0.5B_2$	$1.75L_2$-$0.5B_2$	$1.75L_1$-$0.5B_1$+ $1.75L_2$-$0.5B_2$
Head-on (starboard to a target)	$3.25L_1$-$0.5B_1$	$3.25L_2$-$0.5B_2$	$3.25L_2$-$0.5B_2$	$3.25L_1$-$0.5B_1$+ $3.25L_2$-$0.5B_2$
Crossing ahead of a target on starboard	$3.25L_1$-$0.5B_1$	$6.1L_2$-$0.5L_2$	$6.1L_2$-$0.5L_2$	$3.25L_1$-$0.5B_1$+ $6.1L_2$-$0.5L_2$
Crossing astern of a target, which approached from starboard	$1.75L_1$-$0.5B_1$	$3.9L_2$-$0.5L_2$	$3.9L_2$-$0.5L_2$	$1.75L_1$-$0.5B_1$+ $3.9L_2$-$0.5L_2$
Crossing ahead of a target on port	$1.75L_1$-$0.5B_1$	$6.1L_2$-$0.5L_2$	$6.1L_2$-$0.5L_2$	$1.75L_1$-$0.5B_1$+ $6.1L_2$-$0.5L_2$
Crossing astern of a target, which approached from port	$3.25L_1$-$0.5B_1$	$3.9L_2$-$0.5L_2$	$3.9L_2$-$0.5L_2$	$3.25L_1$-$0.5B_1$+ $3.9L_2$-$0.5L_2$
Overtaking (port to a target or starboard to a target)	$1.75L_1$-$0.5B_1$	$1.75L_2$-$0.5B_2$	$1.75L_2$-$0.5B_2$	$1.75L_1$-$0.5B_1$+ $1.75L_2$-$0.5B_2$

Table 2
Approximated minimum spacing (in metres) for Coldwell's domain if own ship's length and beam are: 160 m, 20 m and target's length and beam are 320 m, 40 m, respectively.

Encounter/Safety condition	Own domain not violated	Target's domain not violated	Neither domain is violated	Domains not overlapping
Head-on (port to a target)	270	540	540	810
Head-on (starboard to a target)	510	1020	1020	1530
Crossing ahead of a target on starboard	510	1792	1792	2302
Crossing astern of a target, which approached from starboard	270	1088	1088	1358
Crossing ahead of a target on port	270	1792	1792	2062
Crossing astern of a target, which approached from port	510	1088	1088	1598
Overtaking (port to a target or starboard to a target)	270	540	540	810

Contemporary ship domain models are often described by multiple parameters responsible for reflecting various factors affecting safe distance in an encounter situation. This is particularly true for domains that have been developed by means of either safety analysis or utilising experts' knowledge. Both of these methods make it possible to investigate the impact of each factor separately which is the condition for turning those factors into model's parameters. The major factors taken into account in various domain models are gathered here in Tables 4 and 5: Table 4 lists those associated with the ships' parameters and Table 5 – situation and environment-related factors. 'N/A' entries in some table cells denote that a certain factor is irrelevant because of the domain's purpose or that cited works do not address this issue directly.

3.1. Empirical ship domain models

As of late, AIS data have been used for domain determination and a project documented by Hansen et al. (2013) is an example of this approach. The research is based on AIS data from Danish waters. The authors have assumed that a domain (Fig. 7) is proportional to the ship's length and analysed the domain's shape by means of intensity plots, which visualize distances between ships. Only encounters where minimal distance between ships was below 3500 m have been taken into account to eliminate those where interaction is unlikely. The results have shown an elliptic shape roughly in accordance with that of Fuji and Tanaka (1971) and Coldwell (1983). Following this, different areas have been chosen to determine domain's length and width, so as to focus on situations in which the navigators are more likely to make an actual decision about the preferred distance:

– A narrow channel of Drogden has been used to determine ellipse's length for ships moving in the same direction within TSS without overtaking.

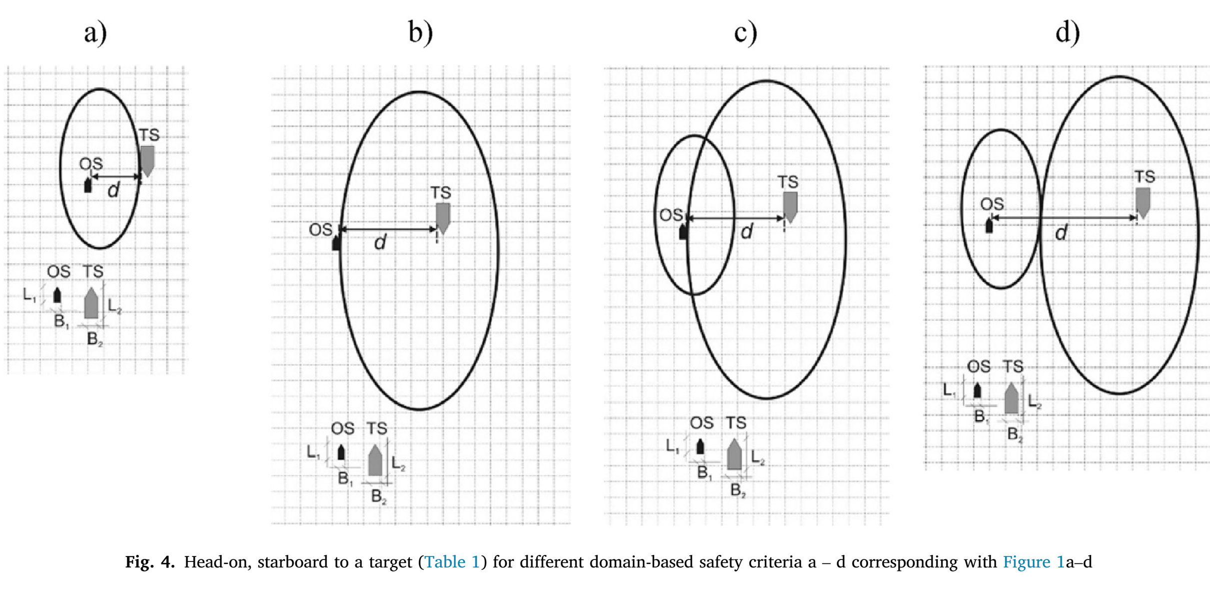

Fig. 4. Head-on, starboard to a target (Table 1) for different domain-based safety criteria a – d corresponding with Figure 1a–d

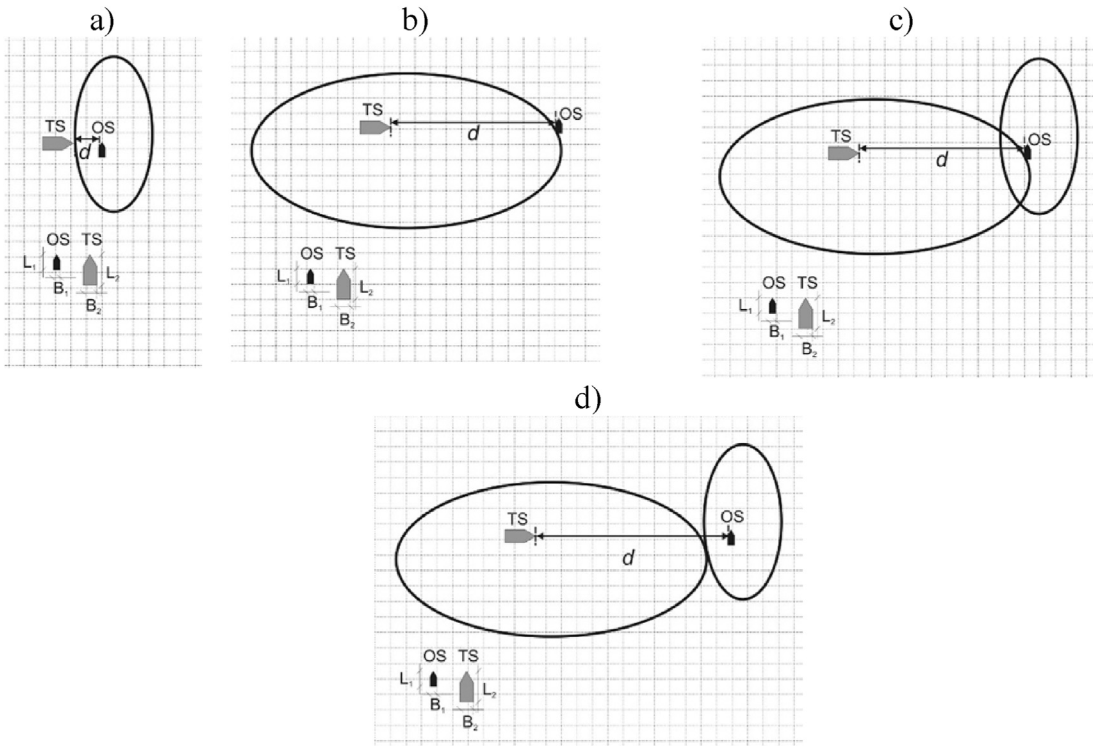

Fig. 5. Crossing ahead of a target on port (Table 1) for different domain-based safety criteria a – d corresponding with Figure 1a–d

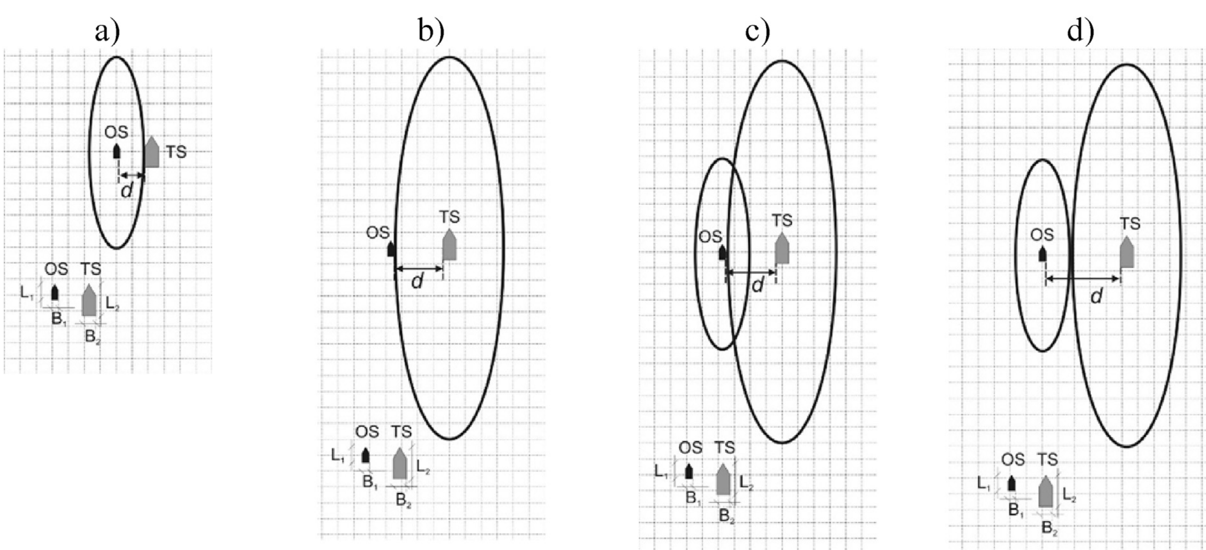

Fig. 6. Overtaking, starboard to a target (Table 1) for different domain-based safety criteria a – d corresponding with Figure 1a–d

– The intersection of main traffic and ferry traffic in Fehmarn Belt strait has been applied for finding domain's length when crossing.
– Route T of Fehmarn Belt and Great Belt bridge have been used for domain's width during overtaking.

The following results have been obtained:

– a distance between two ships or a ship and pylon is usually between 1.4 and 1.8 ship lengths, so 1.6 ship lengths has been chosen for ellipse's semi-minor axis,
– 4 ship lengths have been chosen for semi-major axis, with a ship shifted 0.5 length backwards from the ellipse's centre.

The safe distances in port and starboard directions have been determined only for overtaking (when passing from both sides is allowed by COLREGS), so the distances are equal in both directions. The authors admit that starboard sector would be wider for head-on and crossing encounters. They also suggest that the determined domain dimensions are dictated by traffic conditions and that most navigators would prefer larger spacing, if possible. However, they conclude that the determined domain is well suited for simulating safe traffic in the researched areas. Furthermore, it has been applied for estimating the efficiency of a TSS guiding traffic through the openings of a proposed bridge on Fehmarn Belt (Jensen et al., 2013).

The research documented in (Wang and Chin, 2016) is another

Table 3
Approaches to ship domains by various authors.

Domain by	Safety criterion	Method of determining
Fuji and Tanaka, 1971	Target's domain not violated	Empirical: statistical processing of radar data
Goodwin, 1975	N/A	Empirical: statistical processing of radar data
Davis et al., 1980 and Davis et al., 1982	Own domain not violated	Computer simulation
Coldwell, 1983	Own domain not violated	Empirical: statistical processing of radar data
Zhu et al., 2001	Own domain not violated	Experts' knowledge / neural networks
Pietrzykowski, 2008	Own domain not violated	Experts' knowledge / fuzzy neural networks
Pietrzykowski and Uriasz, 2009	Own domain not violated	Experts' knowledge / fuzzy neural networks
Wang et al., 2010 and Wang, 2013	Own domain not violated	Safety analysis
Hansen et al., 2013	N/A	Empirical: statistical processing of AIS data
Rawson et al., 2014	Domains not overlapping	Safety analysis: local traffic
Wang and Chin, 2016	Domains not overlapping	Empirical: statistical processing of data
Liu et al., 2016	Own domain not violated	Analytical: safety of local traffic
Dinh and Im, 2016	Target domain not violated	Experts knowledge / analytical

example of an empirical ship domain (Fig. 8) proposed for a particular water region (Singapore Port and Singapore Strait). The data has been collected by the Maritime and Port Authority of Singapore and stored in Vessel Traffic Information System (VTIS) database. A total of 624 vessels have been analysed and 264,975 ship encounters within 2 NM range have been found. It has been assumed that domain's size is a linear function of ship's length and a quadratic function of its speed, and the safe distance in each direction depends additionally on the polar angle measured clockwise from the ship heading. The above assumptions have made it possible to find angular dependency as well as the precise values of length and speed coefficients by means of a calibration process utilising the Genetic Algorithm (GA). In the course of this process smaller weights have been assigned to pairs of ships with larger minimal distances so as to decrease their impact on domain's size and shape. The authors assumed a free-form asymmetrical polygon with multiple vertices so as not to be limited by conventional shapes of an off-centred circle or ellipse. The proposed domain is compared with circular, elliptical and polygonal domains in terms of ship separation.

Another specific form of an empirical ship domain has been investigated in (Goerlandt et al., 2016), where authors presented AIS data-based analysis of navigation in ice conditions, where a convoy of vessels follows an ice-breaker. Keeping safe distances between particular ships is necessary there and those distances have been determined depending on the ice conditions.

3.2. Knowledge-based ship domain models

A knowledge-based ship domain may utilize a neural network as has been presented in (Zhu et al., 2001). Zhu's research consisted of two phases: a detailed survey collecting navigators' assessments of various situations followed by developing a back propagation neural network (BPNN), which was then used to generalize the gathered data and shape it into rules. Owing to this approach it was possible to take into account not only own ship's length and target's length but also the manoeuvrability of the own ship as well as COLREGS and weather conditions.

Table 4
Ship-related factors taken into account in various domain models.

Domain by	Own ship's length	Own ship's speed	Own ship's manoeuvrability	Target's length	Target's speed
Fuji and Tanaka, 1971	Yes	No	No	Yes	No
Goodwin, 1975	N/A	No	No	N/A	No
Davis et al., 1980 and Davis et al., 1982	Yes	No	No	No	No
Coldwell, 1983	Yes	No	No	No	No
Zhu et al., 2001	Yes	No	Yes	Yes	No
Pietrzykowski, 2008	Yes	Yes	Yes	N/A	N/A
Pietrzykowski and Uriasz, 2009	Yes	Yes	Yes	Yes	No
Wang et al., 2010 and Wang, 2013	Yes	Yes	Yes	N/A	N/A
Hansen et al., 2013	Yes	No	No	N/A	N/A
Rawson et al., 2014	No (ship type used instead)	Yes	No (ship type used instead)	N/A	N/A
Wang and Chin, 2016	Yes	Yes	No	Yes	Yes
Liu et al., 2016	Yes	Yes	No	No	No
Dinh and Im, 2016	No	Yes (for action area only)	No (target's manoeuvrability)	Yes	Yes (for action area only)

Table 5
Situation and environment-related factors taken into account in various domain models.

Domain by	Encounter type	Weather conditions	Traffic conditions	COLREGS	Human factor
Fuji and Tanaka, 1971	No	Yes	No	No	No
Goodwin, 1975	No	Yes	No	Yes	No
Davis et al., 1980 and Davis et al., 1982	No	No	No	Yes	No
Coldwell, 1983	Yes	No	No	Yes	No
Zhu et al., 2001	No	Yes	No	Yes	No
Pietrzykowski, 2008	No	Yes	Yes	N/A	No
Pietrzykowski and Uriasz, 2009	Yes	Yes	Yes	Yes	No
Wang et al., 2010 and Wang, 2013	No	Yes	Yes	No	Yes
Hansen et al., 2013	No	No	No	N/A	No
Rawson et al., 2014	No	No	No	N/A	No
Wang and Chin, 2016	No	No	No	Yes	No
Liu et al., 2016	No	No	Yes	N/A	No
Dinh and Im, 2016	Yes	No	No	Yes	No

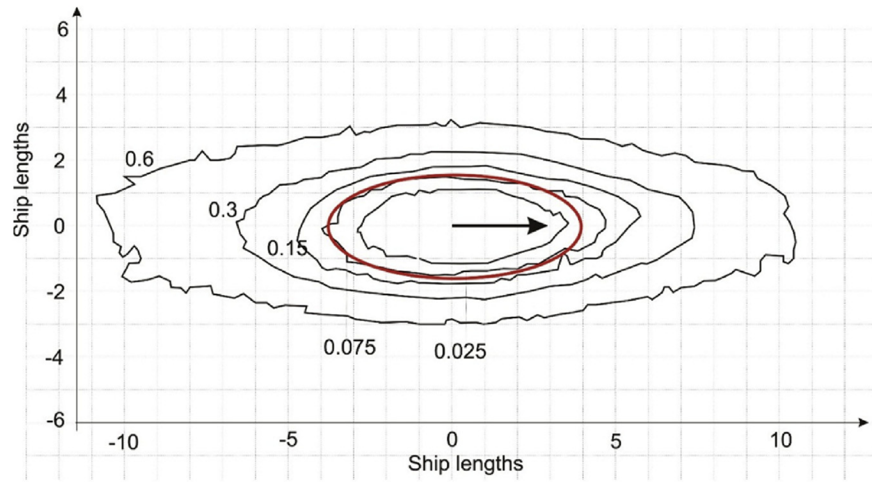

Fig. 7. Domain proposed in (Hansen et al., 2013) together with intensity index plots for values 0.025–0.6.

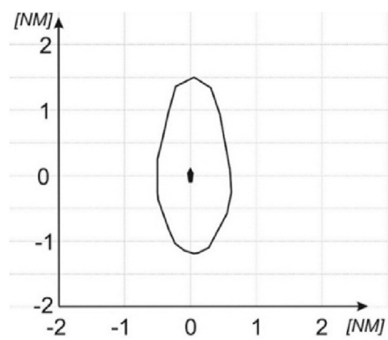

Fig. 8. Domain proposed in (Wang and Chin, 2016) for head-on encounters.

A similar approach has been utilised in (Pietrzykowski, 2008; Pietrzykowski and Uriasz, 2009) – two works dedicated to ship domains for narrow fairways (Fig. 9) and open waters (Fig. 10), respectively. Both papers might be considered combinations and extensions of works by Zhao et al. (1993) and Zhu et al. (2001), as they utilise navigator's knowledge and neural networks to determine fuzzy domains. The main methodological differences have been: distinguishing two fields of application (which lead to more focused reports) and applying fuzzy neural networks. In terms of ship-related factors (Table 4) Pietrzykowski additionally took into account own ship's speed and was one of the first to report the importance of target's relative speed. A progress in situation-specific factors (Table 5) has also been made: encounter type and traffic conditions have been added. However, the main finding of (Pietrzykowski, 2008) was the dependency of the distance between ships and the safety perceived by their navigators. The distance between a ship and the domain boundary has been found to be an exponential function of a safety level, meaning that perceived safety is roughly proportional to the logarithm of a distance instead of a distance itself. This implies that for very small distances safety will increase very fast with the increase of a distance, however for larger distances it will increase much slower and will never reach the highest value. Considering the survey-based data collection there are two possible interpretations of this: navigators may be reluctant to admit that they are safe or they actually never feel fully safe in narrow fairways, no matter the distance to the nearest object. As for the open waters-targeted research (Pietrzykowski and Uriasz, 2009), the impact of both the own ship's and the target's length on the domain was investigated and it was found that smaller ships usually adjust their domains when encountering larger ones. As for the general shape of a domain, both crisp and fuzzy domains were found to be asymmetric, but the level of asymmetry was minor. Crisp domains were polygons and fuzzy ones – irregular shapes sometimes roughly resembling circles (with the own ship moved from the circle's centre towards aft). In both cases the fore sector was much larger than aft sector and domain's shape roughly resembled a circle. Other results of Pietrzykowski and Uriasz indicated that the shape of the domain changes significantly depending on the encounter type: in case of crossing encounters the front sector of the domain is much wider than in case of head-on (Fig. 10a and b).

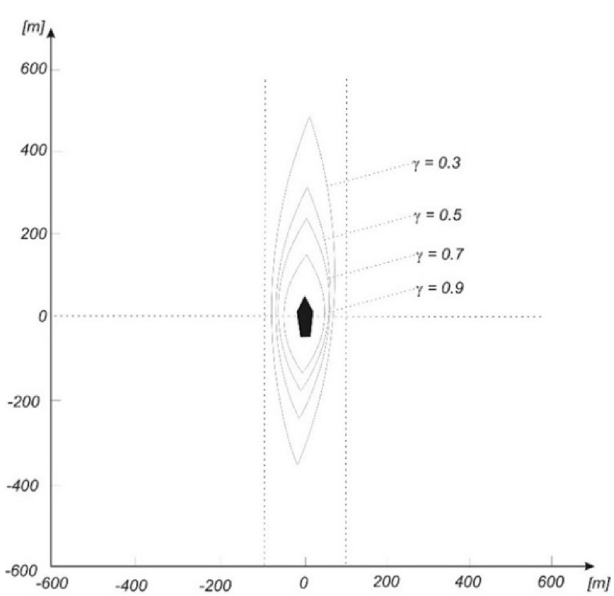

Fig. 9. Fuzzy domain proposed in (Pietrzykowski, 2008) for narrow fairways.

Despite presenting two water region-specific domain models, in (Pietrzykowski and Uriasz, 2009) the authors conclude their report with a suggestion that it is possible to create one universal ship domain. Such a domain should be flexible in terms of shape and size and should take into account all important parameters: types, sizes, manoeuvring parameters and speeds of the own and encountered ships, the type of area, visibility conditions and data credibility. It could be implemented as a default domain in shipboard and shore-based integrated navigational systems and used to estimate navigational risk, determine a safe trajectory of the ship and specify the moment to initiate an evasive action.

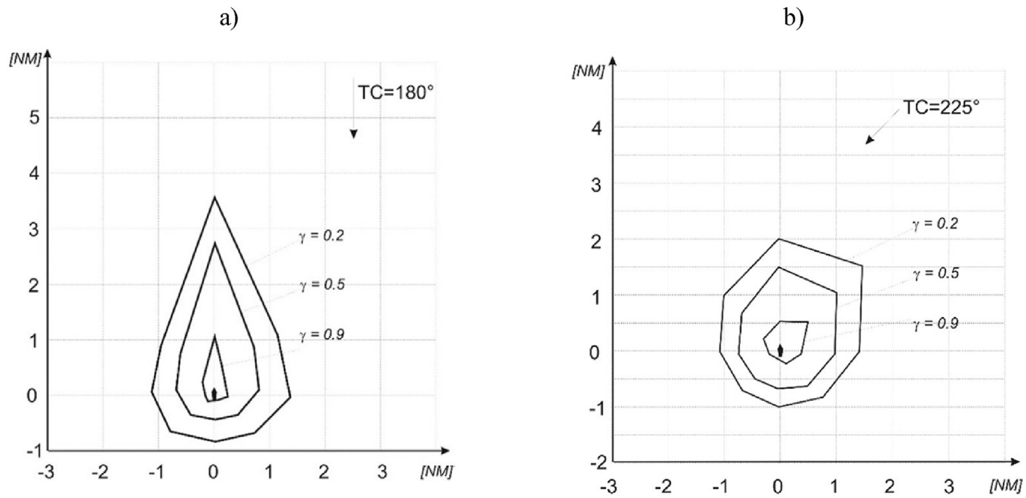

Fig. 10. Fuzzy domain proposed in (Pietrzykowski and Uriasz, 2009) for open sea a) target course equals 180°, b) target course equals 225°.

3.3. Analysis-based ship domain models

One of the first analysis-based publications on ship domains updating the classic models (proposed in 1970s and 1980s) has been presented by Zhao et al. (1993). While the set of domain parameters has not been extended, the paper featured a critical analysis of past domains (Fuji and Tanaka, 1971; Goodwin, 1975; Coldwell, 1983). It also introduced a fuzzy domain. Unlike crisp domains, a fuzzy one can vary between different levels of safety, depending on the depth of predicted domain violation.

A complete analytical domain model has been developed in (Wang et al., 2010). The author has proposed a Quaternion Ship Domain (QSD), presented in Fig. 11, where the size is determined by four radii (i.e. fore, aft, starboard and port) and the shape is modelled by another index parameter. All five parameters are functions of ship's speed, length and manoeuvrability, the latter defined by advance A_D and the tactical diameter D_T. The boundaries of the QSD domain have then been changed from crisp to fuzzy ones, resulting in a fuzzy quaternion ship domain (FQSD), in a similar way as previously done in (Pietrzykowski and Uriasz, 2009). The QSD concept from (Wang et al., 2010) has been further developed by its author in (Wang, 2013), this time as a Dynamic Quaternion Ship Domain (DQSD). DQSD extends QSD so as to consider a number of additional factors: time-varying environment (including traffic circumstances) and human element (navigator's states) as well as to apply Maneuvering Modeling Group (MMG) model for ship manoeuvrability. Accompanying computer simulation illustrated how the dynamic domain re-sizes and re-shapes so as to adjust to circumstances in typical encounter situations.

A quadrilateral ship domain, similar to a particular case of the one from (Wang et al., 2010) has also been proposed in (Dinh and Im, 2016). The domain, called there a ‘blocking area’ is a shape around the target, which is the most dangerous area and should not be violated by the own ship. Its dimensions are based mainly on calculations of the advance distance of the own ship (for all encounters) and additionally the advance distance of the target (for head-on encounters only). Apart from the blocking area, the authors also use the term of an ‘action area’ The latter is a circular area, in which the ship must perform a collision avoidance manoeuvre so as to resolve the encounter situation safely. A similar concept has been developed by in (Krata and Montewka, 2015), where authors consider ship's manoeuvrability to determine by means of a computer simulation a critical area, whose violating makes it impossible to avoid a collision.

In (Rawson et al., 2014) a ship domain dedicated for a particular water region (a part of the River Thames in Central London extending

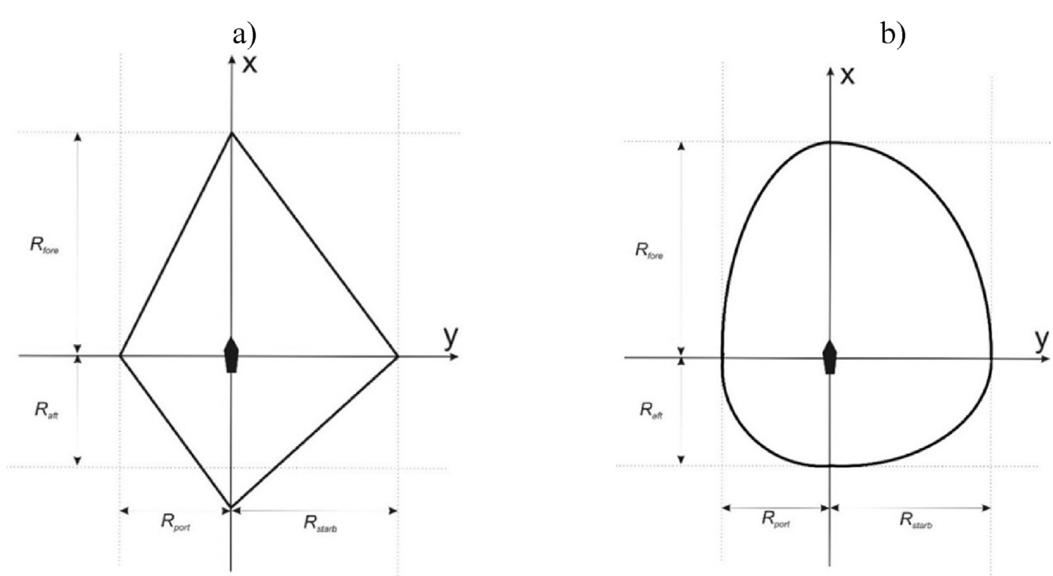

Fig. 11. Quaternion ship domain (QSD) proposed in (Wang et al., 2010) represented by a) quadrangle ship domain, b) combined ellipse ship domain.

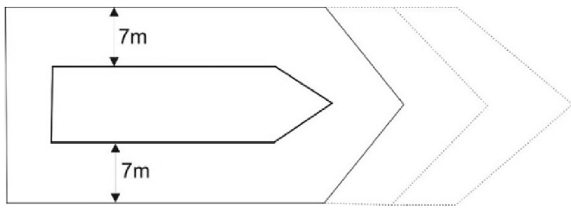

Fig. 12. Domain proposed in (Rawson et al., 2014) with nose extending forward depending on type of vessel and speed over ground.

from Lambeth Bridge to Wapping Ness) has been proposed. Due to the characteristics of the study area, after consultations with stakeholders (Port of London Authority, river users and expert navigators) the domain (Fig. 12) has been arbitrarily set to a 7 m buffer around a ship with a fore sector that extends depending on a reaction distance. It has been assumed that reaction distance is the distance travelled by a ship in 10 s multiplied by a manoeuvrability factor (larger than 1 for less manoeuvrable ships) assigned to a ship type. Thus the domain's total size is a function of only two parameters: ship's speed and ship's type, with the latter one covering both manoeuvrability and length, which are not taken into account separately. Having established a domain model, the researchers carried out an extensive analysis of the safety of traffic based on AIS data provided by a local Vessel Traffic Service.

Another region-specific ship domain model has been proposed for capacity analysis in restricted channels (Liu et al., 2016) and has been dedicated to port of Tianjin – maritime gateway to Beijing. It is a dynamic domain like (Wang, 2013) and has a shape of an ellipse. However, unlike (Hansen et al., 2013), here elliptic shape has been here chosen arbitrarily, instead of empirically. Also lengths of semi-axes have not been determined experimentally, but analytically, separately for various problems typical for the discussed water region. The investigated problems were:

- navigating along the channel,
- crossing the channel,
- joining another flow (possibly traversing through the reverse traffic flow),
- turning (affecting one-way or two-way traffic flow),
- security zones for LNG ships.

Domain's dimensions are here derived from the assumption that the domain around a ship is an area that should remain free in order to prevent collision. E.g. for ships navigating along the channel semi-major axis length is equal to the visual stopping range, which is a sum of a reaction distance, breaking distance and a safe distance set to a quarter of a ship's length. Domain's dimensions are then used for a capacity analysis of a main channel of Tianjin Port: a safe number of ships per year is estimated at about 94,000 but could be enlarged to over 158,000 after proposed broadening of this channel.

3.4. *Ship domain models: discussion*

First, some general limitations of methods belonging to the three groups presented above are briefly discussed below.

Empirical ship domains are determined by data-based methods, which are greatly affected by the type of a water region and particular water area. Water regions usually differ not only in traffic density (affecting the size of ship domains), but also in the percentage of head-on, crossing and overtaking encounters. E.g. in case of narrow waterways the vast majority of encounters will be head-on and overtaking, resulting in smaller than usual separation in port and starboard sectors (because of limited waterway width). In case of Traffic Separation Schemes (TSS) overtaking encounters will dominate, with crossings being much rarer and head-on nearly non-existent (theoretically they should not occur). Unfortunately, some researchers do not provide information on the percentage of different types of encounters or even on the percentage of encounters registered within TSS. The dominance of overtaking encounters within TSS means that passing both port and starboard to the overtaken vessel is allowed by COLREGS, so there will be small, if any, differences between port and starboard sectors of a domain. Another problem is that situations when ships manoeuvre usually are not representative for ship domain sizes. Manoeuvres are mostly initiated in advance (especially if they are limited in volume due to the width of a waterway) so the resulting separation between ships may be much larger than one that would be acceptable in an encounter, where no ship manoeuvres. Additionally, for head-on encounters the effective separation will be roughly doubled, because both ships are obliged to manoeuvre and each ship's manoeuvre is supposed to be sufficient.

As for knowledge-based determination of ship domains, the method is obviously heavily dependent on the choice of surveyed navigators (even experts' judgments are subjective) as well as on the choice of the survey questions and scenarios. Subjectivity is also the problem of analysis-based domains. Here the results rely on many assumption (some of which are disputable) and multiple factors taken into account by researchers depending on their preferences.

Comparing the results obtained by particular researchers, the following can be observed. Contemporary domain shapes are similar to some of the classic ones, especially the empirical ones, which are bound to remain relatively simple (a few basic parameters including ship's length and speed), because it is practically impossible to determine a function of a larger number of variables based on empirical data. In a such relatively simple empirical model by (Hansen et al., 2013) the shape of an ellipse resembles the one proposed by (Fuji and Tanaka, 1971; Coldwell, 1983), with the its length-dependant dimensions being close to that of (Coldwell, 1983). This similarity is further strengthened by the statement of (Hansen et al., 2013) that most navigators would prefer larger spacing and that in particular the starboard sector would probably be wider for head-on and crossing encounters.

The domain model according to (Wang and Chin, 2016) despite also being based on statistically processed empirical data, brings more parameters than (Hansen et al., 2013) and related older models (Fuji and Tanaka, 1971; Goodwin, 1975) and its complexity can be compared to that of (Pietrzykowski and Uriasz, 2009). Wang and Chin take into account the own ship's length and speed, but they assume that domains should not encroach, which means that the effective spacing is affected by both ships' lengths and speeds. The authors further claim that the superiority of their domain results from the free-form polygonal shape, but that is debatable. First, the resulting polygon is actually quite close to an ellipse – a shape suggested by past works (Fuji and Tanaka, 1971; Coldwell, 1983; Hansen et al., 2013). Second, the criterion of not overlapping (used here) makes it hard to compare the effective spacing between ships with that resulting from using other domains. Also, differences in results can be partly attributed to different water regions that provided data sets.

The shape of a knowledge-based domain by (Pietrzykowski and Uriasz, 2009) resembles the off-centred circle proposed by Davis et al. (1980), which was also based on computer simulation rather than empirical data. However, for crossing encounters the domain's dimensions were closer to the off-centred ellipse reported in (Coldwell, 1983): the front sector of the domain was much wider than in case of head-on. This is understandable, considering that for head-on the lateral component of the target's relative speed is much smaller than for crossing. In general (Pietrzykowski and Uriasz, 2009), take into account more factors and postulate that by further increasing their number a universal ship domain may be proposed.

Pietrzykowski's postulate concerning a universal domain may have inspired Wang (Wang et al., 2010; Wang, 2013) who has developed a model very much in line with it. As for now it is the most complex ship domain model and it takes into account the largest number of parameters. However, it is not without limitations. The research has been purely analytical and it may be argued that it produced a “desired” domain, which may be impractical if there is not enough sea room to use it. Also, large number of parameters can make the domain inconvenient, as some parameter values may have to be updated often (new values for every officer of the watch, every water region and every change of environmental conditions or change in motion parameters). Finally, target's length and speed are mentioned there as parameters taken into account, but they are absent in the formulas presented in the paper, where only own ship's parameters are used.

The complexity of models by (Pietrzykowski and Uriasz, 2009; Wang et al., 2010; Wang, 2013) was found impractical by (Rawson et al., 2014), where the number of parameters was reduced like in (Hansen et al., 2013), the shape was simplified and the size was only a 7 m buffer due to the nature of traffic on Thames. But it must be noted that a criterion of not overlapping domains has been applied, so a 7 m buffer in practice translates to a spacing of 14 m when passing side by side or 14 m plus reaction distance component when approaching from behind or head-on (crossing is relatively rare in the discussed area due to the shape of a waterway). While the domain proposed in (Rawson et al., 2014) is much smaller than any presented by other researchers it is somewhat in accordance with the logarithmic dependency reported by (Pietrzykowski, 2008). Small domain here is an effective one, which means that navigators do not necessarily have to feel safe with such small distances but rather that they cannot expect more given the circumstances. It may be argued that this domain is a particular case of Pietrzykowski's domain for relatively low safety and a different domain criterion (not violating a domain is replaced here with domains not overlapping).

The analysis-based and region-specific approach to domain by (Liu et al., 2016) is generally similar to that of Rawson et al. (2014), but more advanced dependencies are applied to establish precise dimension values, especially in case of intersections of traffic (crossing the channel or joining another flow). Unfortunately, in (Liu et al., 2016) the resulting domain dimensions are not given explicitly so a direct comparison cannot be made.

As for atypical ship domains, both the ‘action area’ by (Dinh and Im, 2016) and area determined in (Krata and Montewka, 2015) are not domains in the sense of Goodwin's definition. They are actually much closer to the concept of arena (Davis et al., 1982) – the area, whose entering should trigger a collision avoidance action so as to avoid violating the actual domain.

Generally, despite certain similarities, the domain models listed in Section 3 can differ significantly from each other, especially if they have been developed with a particular water area or a specific purpose in mind. However, some shape patterns can be easily distinguished (e.g. ellipses and off-centred circles) and they show strong similarities to those from the past despite the evolution of methods and research tools. Additionally, it is worth mentioning that every domain listed in Section 3 can be turned into a so called 3D domain by adding two extra parameters covering ship's draft and air draft respectively. In practice, applying a ship domain, which includes draft, involves using detailed bathymetric data and checking whether the water depth is sufficient for a given draft. Analogically, in case of air draft, it must be checked, whether a ship can safely cross under bridges and similar objects of known heights.

Finally, a ship domain-related problem that is still being researched is that of ships' trajectory estimation. Even though some authors of ship domain models (Zhu et al., 2001; Pietrzykowski, 2008; Pietrzykowski and Uriasz, 2009; Wang et al., 2010; Wang, 2013) take into account ships manoeuvrability, its precise impact on domains' shapes and dimensions has not been sufficiently documented. In (Krata and Montewka, 2015) own ship's manoeuvring abilities are used to determine a critical area around a ship, but this area is not a domain in the strict sense. Similarly, the fact that manoeuvring vessels do not approach in straight lines has not been sufficiently taken into account. A research on estimations and predictions of ship trajectories has been presented among others in (Perera and Soares, 2010; Perera et al., 2012) and it would be beneficial to apply it to ship domains, considering that the concept of ship domain relates to close encounters, where exact distances between ships are of key importance.

4. Applications of ship domains

Considering the abundance of papers on ship domains it is interesting to investigate their actual impact on collision avoidance, near-miss detection, waterway risk analysis and capacity analysis. Below some works referring to abovementioned ship domain applications are briefly commented on.

4.1. Collision avoidance

While research projects on collision avoidance referring to ship domains are numerous, the cases where ship domains are actually used, not just mentioned, are relatively rare. Safe distance dominates in this kind of projects (Tam et al., 2009; Tam and Bucknall, 2013; Zhang et al., 2015a; Perera and Soares, 2015; Lee et al., 2015; Pietrzykowski et al., 2016) and is considered an industry standard in on-board systems (Chin and Debnath, 2009). When actual ship domains are applied for collision avoidance, they are either older models or largely simplified versions of the contemporary ones.

A domain according to (Fuji and Tanaka, 1971) has been applied in (Chang et al., 2003), where a grid representation of a domain is used for determining optimal safe paths on raster charts. In (Kao et al., 2007), a VTS-dedicated fuzzy logic method of collision avoidance has been introduced: a simple circular ship domain is used there, with a radius equal to a safe distance. The domain's radius is dependent on the linguistic values of own ship's length (small, medium or large), own speed (slow, middle or fast) and sea state (gentle, medium, rough), which are input variables of a fuzzy logic system. Applying a ship domain is also mentioned in (Tsou et al., 2010) where a collision avoidance method based on genetic algorithm (GA) and taking into account COLREGS is presented. However, again a circular domain is applied and COLREGS are handled separately. This research is continued in (Tsou, 2016), where collision avoidance method is combined with the use of ECDIS. The domain remains a circle with a radius set arbitrarily to 1.5 nautical mile. A similar safety ring is also applied in (Zhang et al., 2015a), where a distributed anti-collision system compliant with COLREGS is proposed. Additionally, a circular equivalent of an arena (Davis et al., 1982), called there ‘action range’ is used there – it is set to 6 NM with a possibility to enlarge if a larger domain is expected to remain free of other objects. The radius of a circular domain is said to be depend on multiple factors: vessel size, type of water region, weather conditions, traffic density and the experience of the OOW. In practice, however, it is set arbitrarily to 1.5 NM, with a possibility to adjust it depending on OOW's personal preferences.

A modified version of a domain by Coldwell (1983) has been used for evolutionary planning of cooperative safe ship tracks within TSS (Szlapczynski, 2013) and in restricted visibility (Szlapczynski, 2015). The same domain has also been applied in decision support tools visualizing possible collision avoidance manoeuvres (Szlapczynski and Szlapczynska, 2015, 2017) and was a basis for an analysis of domain-related collision risk parameters, which included a time to domain violation (Szlapczynski and Szlapczynska, 2016). Lazarowska (2015) has presented a method of planning a safe trajectory of a ship, based on Ant Colony Optimisation. The method uses a hexagonal domain of a target inspired by (Smierzchalski and Michalewicz, 2000), though the possibility of applying other shapes (including an ellipse) is mentioned. In a later paper (Lazarowska, 2016) the author presents a deterministic approach to the same problem. Again hexagonal ship domain is used, this time with the dimensions being dependent on visibility and weather conditions.

4.2. Near miss detection and trajectory processing

In (van Iperen, 2015) crossing, overtaking and head-on close encounters on the North Sea have been researched based on the intrusion of a ship's relative domain. The relative domain is defined there as the 0.5% percentile contour, that is an area around a ship, which is violated by only 0.5% of the passing targets. The research applies the concept of a ship domain while at the same time identifying an empirical domain for the North Sea. The latter is done in a similar mode to (Hansen et al., 2013; Wang and Chin, 2016) and with similar results in terms of shape (elliptic shapes for overtaking and head-on encounters), but significantly larger: from 6 lengths in front of the ship for overtaking to 20 lengths for head-on and around 3 to 4 ship lengths at the side for both overtaking and head-on. A study on near misses for the same water area has been presented in (van Westrenen and Ellerbroek, 2017). A bow-centred ship domain with dimensions as in (Fuji and Tanaka, 1971) has been applied there to investigate the impact of complex multi-ship conflicts on the number of close quarter situations. The same domain (only ship-centred) has been used for conflicts detection in Southeast Texas waterway, as documented in (Wu et al., 2016). It has also been applied in (Zhang et al., 2016a), but the ship domain has been there supplemented by a number of other situational characteristics to obtain a greater precision of identifying near miss ship collisions.

A related example of applying a ship domain has been provided in (Zhang et al., 2016b). The paper introduces a method of simplifying AIS-derived ship trajectories so as to reduce their data storage in maritime databases. The acceptable threshold of a simplification is determined by a ship domain's dimensions to ensure that the difference between the simplified trajectory and the original trajectory is within the safety scope. A quick method of determining a length-dependent ship domain is also proposed there – it is a simplified version of the method presented by Hansen et al. (2013).

4.3. Waterway risk analysis

Until recently, the basic criterion of safe distance was usually applied to research on waterway risk and related problem of waterway capacity analysis (Chin and Debnath, 2009; Wen et al., 2015; Zhang et al., 2015b; Li and Pang, 2013; Sang et al., 2015; Xiao et al., 2015; Goerlandt et al., 2012). However, it is changing and more refined approaches are also tried. Among others, the previously mentioned near miss detection methods may be further utilised for investigating waterway risk. Such a method utilising a fuzzy quaternion ship domain according to (Wang et al., 2010) combined with a criterion of domain overlaps is applied in (Qu et al., 2011) for assessment of collision risk in the Singapore Strait, based on the AIS data. The research on collision risk in that area has been continued in (Weng et al., 2012), where a circular ship domain according to (Mou et al., 2010) has been used. In (Goerlandt and Kujala, 2014) various approaches to collision risk analysis are compared and assessed, including the above methods of (Qu et al., 2011; Weng et al., 2012) and the previously mentioned domains according to (Wang et al., 2010; Mou et al., 2010) are used there respectively. This comparison and review research has then been continued in (Goerlandt and Montewka, 2015) also utilising the fuzzy quaternion ship domain according to (Wang et al., 2010).

5. Other ship domain-related research: collision risk index and risk level

The concepts of collision risk index (CRI) and risk level are ship domain's main rivals, especially in collision avoidance research. CRI is a single crisp or fuzzy value reflecting the risk of collision with other ships. Usually it is a cost-like value (the higher index value, the higher the collision risk). The history of CRI has been presented in (Xu et al., 2016), where proposed CRI is dependent on DCPA, TCPA and own speed. A more complex way of determining CRI has been introduced in (Gang et al., 2016), where it is a function of: TCPA, DCPA, relative distance between the ships, relative bearing and velocity ratio of two vessels. Similarly to ship domain, CRI can also be dedicated to a particular region: in (Qu et al., 2011) the authors proposed macro (area-oriented) and micro (single encounter-oriented) CRI for the Singapore Strait. Among others, macro CRI presented there used vessel speed dispersion as a main parameter, while micro CRI was heavily affected by a degree of acceleration and deceleration. A crisp collision risk index has also been proposed in (Perera and Soares, 2015), where the vector product between the unit vectors of the relative course-speed and bearing vectors is categorized as the collision risk (CR) between the vessels.

The concept of a risk level is particularly popular among designers of Collision Alert Systems (CAS). CAS is a decision-support tool, which, in maritime industry can be designed either for ship navigators or VTS centre operators, aiming at alerting the users on possible vessel collisions via visual, sound or informative signals (IMO, 2007). Unlike a typical collision avoidance system (also in some publications abbreviated the same way, which might be misleading) a CAS is focused on collision risk assessment and alerting rather than proposing collision avoidance manoeuvres.

In (Baldauf et al., 2011) the authors propose a general CAS framework offering four output levels of a collision risk (developing risk of collision, existing risk of collision, developing danger of collision, existing danger of collision), corresponding with the IMO performance standards for Integrated Navigation Systems recommendations (IMO, 2007). A general risk model for situation assessment is based on a safe distance parameter, COLREGS compliance, visibility (good/restricted), type of a water region (open or restricted waters), wind and current. A continuation of this research has been documented in (Baldauf et al., 2015), where it is investigated whether and how the Airborne Collision Avoidance System (ACAS) can be implemented to maritime collision avoidance. Following ACAS's three-level alerting scheme (caution, warning and collision areas), the authors validate that a maritime ACAS-like solution indeed can be designed. A proposal of potential transfer of aviation solutions to shipping is presented via predictions of ship manoeuvring areas (Potential Area of Water method with Nomoto model applied). Risk assessment is based on quantification of collision risk by utilization of the ratio of overlapping areas.

In (Bukhari et al., 2013) a CAS-related solution is presented, which calculates the degree of collision risk in range [-1.0; +1.0] based on radar data from VTS. It takes into account DCPA, TCPA and variation of compass degree (VCD). A fuzzy inference rules are then applied to determine the degree of collision risk in terms of linguistic value (positive small, positive medium small, positive big, negative small, negative medium small, negative big, positive medium big). In (Simsir et al., 2014) the authors propose a CAS-like framework based on Artifical Neural Networks (ANN) and intended for reciprocally passing vessels in narrow straits (tested for the Istanbul Strait). It features one output level of collision risk (safe/risk exists) reporting any existing risk of collision for a ship's 3-min-onward positions. Finally, in (Goerlandt et al., 2015) an advanced Risk-Informed CAS (RICAS) is proposed, where an encounter is analysed in relation to: COLREGS, imminence of accident occurrence, deviations from a reference level and ambiguous situations. The risk level value is dependent there on multiple parameters, including: DCPA, TCPA, Bow Cross Range (BCR), Bow Cross Time (BCT), relative bearing, range, time of day (day/night) and visibility (poor/good). A membership function is defined for each parameter and the parameters are then processed by a fuzzy expert system, where final risk levels (safe, caution, warning and alarm) are assigned by means of fuzzy rules.

A related research on collision risk is presented in (Lopez-Santander and Lawry, 2017), where the authors propose a non-linear ship collision risk model based on questionnaires designed to elicit information from mariners. The users were asked to assess risk level according to their experience in given encounter situations defined either by parameters only (the first part of the questionnaire) or also graphically (the second part). Data from around 8000 scenarios were collected in this research and further processed statistically by the Order Probit Model. The result of the research is a model offering a preliminary risk cost function, which can be utilised for path finding and optimisation algorithms to avoid the projected risk of collision in ship encounter situations.

Considering the rapid development of abovementioned methods determining Collision Risk Index (CRI) and risk assessment methods used in Collision Alert Systems (CAS), some comparison of ship domains and those methods can be made. CRI's main advantage is the possibility to aggregate multiple parameters into just one number, based on which decisions are made. Methods applied in CAS usually use a wide array of tools (e.g. fuzzy expert systems) to determine a risk level. Both kinds of methods are very flexible and none of them is limited by a geometrical shape, the way domain is. But the abovementioned limitation is also domain's main strength: a graphical shape may be more intuitional and navigator may feel comfortable knowing what spacing around a ship is assumed by a system. Furthermore, a domain enables a navigator to easily configure the system by adjusting domain dimensions and see the effect of such adjustment instantly onscreen in the domain's shape and size. However, the above mentioned is only true as long as domain models are simple enough to be widely understood by the maritime industry.

6. Conclusions

In the paper a number of ship domain models have been discussed, with an emphasis on the contemporary ones. As the paper shows, the domains differ not only in size and shape but also in their purposes and definitions (safety criteria). Different sizes and shapes, accentuated by some researchers are usually a natural consequence of different purposes or different research methods that have been applied by domains' authors. Factors taken into account in various domain models are usually more meaningful than exact domain shapes: the latter are often overemphasized in literature.

Based on the newest literature in the field it is possible to observe certain trends concerning developing and applying ship domain models. The number of very recent published works on ship domains is a definite evidence of the continuous development of this genre of the maritime science. This includes all three groups of methods listed in Section 3. Region-specific empirical models are being proposed for new water areas (Hansen et al., 2013; Wang and Chin, 2016), while authors of analytical models (Wang et al., 2010; Wang, 2013; Krata and Montewka, 2015; Liu et al., 2016) are trying to address some issues (e.g. dynamics of ship maneuverings and navigating within Traffic Separation Schemes) more accurately. At the same time human judgment and perception of collision risk are being modelled by methods, which use artificial intelligence tools to process expert knowledge and determine human-intuitive ship domains with greater precision.

As for the types of water areas, contemporary ship domains cover all of them. Apart from the models dedicated to open waters (Pietrzykowski and Uriasz, 2009), restricted waters (Hansen et al., 2013; Wang and Chin, 2016) and narrow channels (Pietrzykowski, 2008), domain-oriented research also addresses navigating in ice (Goerlandt et al., 2016). Additionally, some researchers postulate that a universal domain, covering all types of water areas, can be proposed (Pietrzykowski and Uriasz, 2009; Wang, 2013). The practical usability of such a model is debatable though. If applied in a collision avoidance system, it would require complex and frequent re-configuration, considering the dynamic nature of environment, human element and other parameters listed before. It may be a serious discouraging factor for the navigators and may result in opting for a simpler model, configured arbitrarily by a user (Rawson et al., 2014).

While ship domains have originally been developed mostly for collision avoidance purposes and capacity analysis, the scope of their applications have evolved. As for collision avoidance, after nearly four decades since the term of ship domain was introduced (Fuji and Tanaka, 1971), only a partial success of this concept can be observed. A safe distance (and related measures of TCPA and DCPA) are usually used in real time maritime systems, probably for the simplicity of implementation and interpretation. Ship domains' applications in capacity analyses are more often and more varied, though usually the models used there are dedicated ones (developed by the authors of these analyses) rather than already existing ones. However, those existing models are successfully applied for AIS data-based detection of ship conflicts and near miss collisions, for processing AIS-derived ship trajectories and for analyses of waterway risk. It is especially meaningful that some advanced contemporary ship domains, e.g. the one by (Wang et al., 2010), are applied there. In general, it may be stated that ship domains are systematically growing popular in projects, where accuracy of modeling and assessment is more important than computational time and quick decision-making.

References

Baldauf, M., Benedict, K., Fischer, S., Motz, F., Schröder-Hinrichs, J.-U., 2011. Collision avoidance systems in air and maritime traffic. Proc. Inst. Mech. Eng. Part O J. Risk Reliab 3/225, 333–343.

Baldauf, M., Mehdi, R., Deeb, H., Schröder-Hinrichs, J.U., Benedict, K., Krüger, C., Fischer, S., Gluch, M., 2015. Manoeuvring areas to adapt ACAS for the maritime domain. Sci. J. Marit. Univ. Szczecin 43 (115), 39–47.

Bukhari, A.C., Tusseyeva, I., Lee, B.-G., Kim, Y.-G., 2013. An intelligent real-time multi-vessel collision risk assessment system from VTS view point based on fuzzy inference system. Expert Syst. Appl. 40, 1220–1230.

Chang, K.Y., Jan, G.E., Parberry, I., 2003. A method for searching optimal routes with collision avoidance on raster charts. J. Navig. 56, 371–384.

Chin, H.C., Debnath, A.K., 2009. Modeling perceived collision risk in port water navigation. Saf. Sci. 10/47, 1410–1416.

Cockcroft, A.N., Lameijer, J.N.F., 2011. A Guide to Collision Avoidance Rules. Butterworth-Heinemann, Oxford, UK.

Coldwell, T.G., 1983. Marine traffic behaviour in restricted waters. J. Navig. 36, 431–444.

Davis, P.V., Dove, M.J., Stockel, C.T., 1980. A computer simulation of marine traffic using domains and arenas. J. Navig. 33, 215–222.

Davis, P.V., Dove, M.J., Stockel, C.T., 1982. A computer simulation of multi-ship encounters. J. Navig. 35, 347–352.

Dinh, G.H., Im, N., 2016. The combination of analytical and statistical method to define polygonal ship domain and reflect human experiences in estimating dangerous area. Int. J. e-Navig. Mar. Econ. 4, 97–108.

Fuji, J., Tanaka, K., 1971. Traffic capacity. J. Navig. 24, 543–552.

Gang, L., Wang, Y., Sun, Y., Zhou, L., Zhang, M., 2016. Estimation of vessel collision risk index based on support vector machine. Adv. Mech. Eng. 8 (11), 1–10.

Goerlandt, F., Kujala, P., 2014. On the reliability and validity of ship–ship collision risk analysis in light of different perspectives on risk. Saf. Sci. 62, 348–365.

Goerlandt, F., Montewka, J., 2015. Maritime transportation risk analysis: review and analysis in light of some foundational issues. Rel. Eng. Syst. Saf. 138, 115–134.

Goerlandt, F., Montewka, J., Kuzmin, V., Kujala, P., 2015. A risk-informed ship collision alert system: framework and application. Saf. Sci. 77, 182–204.

Goerlandt, F., Montewka, J., Zhang, W., Kujala, P., 2016. An analysis of ship escort and convoy operations in ice conditions. Saf. Sci. http://dx.doi.org/10.1016/j.ssci.2016.01.004.

Goerlandt, F., Ståhlberg, K., Kujala, P., 2012. Influence of impact scenario models on collision risk analysis. Ocean. Eng. 47, 74–87.

Goodwin, E.M., 1975. A statistical study of ship domains. J. Navig. 28, 328–344.

Hansen, M.G., Jensen, T.K., Lehn-Schiøler, T., Melchild, K., Rasmussen, F.M., Ennemark, F., 2013. Empirical ship domain based on AIS data. J. Navig. 66, 931–940.

IMO, 1972. Convention on the International Regulations for Preventing Collisions at Sea. International Maritime Organization [with amendments adopted from December 2009].

IMO, 2007. Adoption of the Revised Performance Standards for Integrated Navigation Systems (INS). Resolution MSC 83/23/Add.3-ANNEX 30.

van Iperen, W.H., 2015. Classifying ship encounters to monitor traffic safety on the North sea from AIS data. TransNav, Int. J. Mar. Navig. Saf. Sea Transp. 9 (1), 51–58.

Jensen, T.K., Hansen, M.G., Lehn-Schiøler, T., Melchild, K., Rasmussen, F.M., Ennemark, F., 2013. Free flow–efficiency of a one-way traffic lane between two pylons. J. Navig. 66, 941–951.

Kao, S.L., Lee, K.-T., Chang, K.-Y., Ko, M.-D., 2007. A fuzzy logic method for collision avoidance in vessel traffic Service. J. Navig. 60, 17–31.

Krata, P., Montewka, J., 2015. Assessment of a critical area for a give-way ship in a collision encounter. Arch. Transp. 34 (2), 51–60.

Lazarowska, A., 2015. Ship's trajectory planning for collision avoidance at sea based on Ant Colony optimisation. J. Navig. 68, 298–307.

Lazarowska, A., 2016. A new deterministic approach in a decision support system for ship's trajectory planning. Expert Syst. Appl. http://dx.doi.org/10.1016/j.eswa.2016.11.005.

Lee, T., Kim, H., Chung, H., Bang, Y., Myung, H., 2015. Energy efficient path planning for a marine surface vehicle considering heading angle. Ocean. Eng. 107, 118–131.

Li, B., Pang, F.-W., 2013. An approach of vessel collision risk assessment based on the D–S evidence theory. Ocean. Eng. 74, 16–21.

Liu, J., Zhou, F., Li, Z., Wang, M., Liu, R.W., 2016. Dynamic ship domain models for capacity analysis of restricted water channels. J. Navig. 69, 481–503.

Lopez-Santander, A., Lawry, J., 2017. An ordinal model of risk based on Mariner's judgement. J. Navig. 70 (2), 309–324.

Mou, J.M., van der Tak, C., Ligteringen, H., 2010. Study on collision avoidance in busy waterways by using AIS data. Ocean. Eng. 37, 483–490.
Perera, L.P., Oliveira, P., Guedes Soares, C., 2012. Maritime traffic monitoring based on vessel detection, tracking, state estimation, and trajectory prediction. IEEE Trans. Intell. Transp. Syst. 13, 1188–1200. http://dx.doi.org/10.1109/TITS.2012.2187282.
Perera, L.P., Soares, C.G., 2010. Ocean vessel trajectory estimation and prediction based on extended kalman filter. Second Int. Conf. Adapt. Self Adapt. Syst. Appl. 14–20.
Perera, L.P., Soares, C.G., 2015. Collision risk detection and quantification in ship navigation with integrated bridge systems. Ocean. Eng. 109, 344–354.
Pietrzykowski, Z., 2008. Ship's fuzzy domain – a criterion for navigational safety in narrow fairways. J. Navig. 61, 499–514.
Pietrzykowski, Z., Uriasz, J., 2009. The ship domain – a criterion of navigational safety assessment in an open sea area. J. Navig. 62, 93–108.
Pietrzykowski, Z., Wolejsza, P., Borkowski, P., 2016. Decision support in collision situations at sea. J. Navig. http://dx.doi.org/10.1017/S0373463316000746.
Qu, X., Meng, Q., Suyi, L., 2011. Ship collision risk assessment for the Singapore Strait. Accid. Anal. Prev. 43 (6), 2030–2036.
Rawson, A., Rogers, E., Foster, D., Phillips, D., 2014. Practical application of domain analysis: port of London case study. J. Navig. 67, 193–209.
Sang, L.-Z., Wall, A., Yan, X.-P., Wang, J., 2015. A novel method for restoring the trajectory of the inland waterway ship by using AIS data. Ocean. Eng. 110 (Part A), 183–194.
Simsir, U., Amasyali, M.F., Bal, M., Çelebi, U.B., Ertugrul, S., 2014. Decision support system for collision avoidance of vessels. Appl. Soft Comp. 25, 369–378.
Smierzchalski, R., Michalewicz, Z., 2000. Modelling of ship trajectory in collision situations by an evolutionary algorithm. IEEE Trans. Evol. Comput. 4, 227–241.
Szlapczynski, R., 2013. Evolutionary sets of safe ship trajectories within traffic separation schemes. J. Navig. 66, 65–81.
Szlapczynski, R., 2015. Evolutionary planning of safe ship tracks in restricted visibility. J. Navig. 68, 39–51.
Szlapczynski, R., Szlapczynska, J., 2015. A target information display for visualising collision avoidance manoeuvres in various visibility conditions. J. Navig. 68, 1041–1055.
Szlapczynski, R., Szlapczynska, J., 2016. An analysis of domain-based ship collision risk parameters. Ocean. Eng. 126, 47–56.
Szlapczynski, R., Szlapczynska, J., 2017. A method of determining and visualizing safe motion parameters of a ship navigating in restricted waters. Ocean. Eng. 129, 363–373.
Tam, C.K., Bucknall, R., 2013. Cooperative path planning algorithm for marine surface vessels. Ocean. Eng. 57, 25–33.
Tam, C.K., Bucknall, R., Greig, A., 2009. Review of collision avoidance and path planning methods for ships in close range encounters. J. Navig. 62, 455–476.
Tsou, M.-C., Kao, S.-L., Su, C.-M., 2010. Decision support from genetic algorithms for ship collision avoidance route planning and alerts. J. Navig. 63, 167–182.
Tsou, M.-C., 2016. Multi-target collision avoidance route planning under an ECDIS framework. Ocean. Eng. 121, 268–278.
Wang, N., Meng, X., Xu, Q., Wang, Z., 2010. An intelligent spatial collision risk based on the quaternion ship domain. J. Navig. 63, 733–749.
Wang, N., 2013. A novel analytical framework for dynamic quaternion ship domains. J. Navig. 66, 265–281.
Wang, Y., Chin, H.C., 2016. An empirically-calibrated ship domain as a safety criterion for navigation in confined waters. J. Navig. 69, 257–276.
Wen, Y., Huang, Y., Zhou, C., Yang, J., Xiao, C., Wu, X., 2015. Modelling of marine traffic flow complexity. Ocean. Eng. 104, 500–510.
Weng, J., Meng, Q., Qu, X., 2012. Vessel collision frequency estimation in the Singapore strait. J. Navig. 65, 207–221.
van Westrenen, F., Ellerbroek, J., 2017. The effect of traffic complexity on the development of near misses on the North sea. IEEE Trans. Syst. Man, Cybern. Syst. http://dx.doi.org/10.1109/TSMC.2015.2503605.
Wu, X., Mehta, A.L., Zaloom, V.A., Craig, B.N., 2016. Analysis of waterway transportation in Southeast Texas waterway based on AIS data. Ocean. Eng. 121, 196–209.
Xiao, F., Ligteringen, H., van Gulijk, C., Ale, B., 2015. Comparison study on AIS data of ship traffic behaviour. Ocean. Eng. 95, 84–93.
Xu, X., Geng, X., Wen, Y.Q., 2016. Modelling of ship collision risk index based on complex plane and its realization. TransNav, Int. J. Mar. Navig. Saf. Sea Transp. 10 (2), 251–256.
Zhang, J., Zhang, D., Yan, X., Haugen, S., Guedes Soares, C., 2015a. A distributed anti-collision decision support formulation in multi-ship encounter situations under COLREGs. Ocean. Eng. 105, 336–348.
Zhang, W., Goerlandt, F., Kujala, P., Wang, Y., 2016a. An advanced method for detecting possible near miss ship collisions from AIS data. Ocean. Eng. 124, 141–156.
Zhang, W., Goerlandt, F., Montewka, J., Kujala, P., 2015b. A method for detecting possible near miss ship collisions from AIS. Ocean. Eng. 107, 60–69.
Zhang, S.-K., Liu, Z.-J., Wu, Z.-L., Shi, G.-Y., 2016b. AIS trajectories simplification and threshold determination. J. Navig. 69, 729–744.
Zhao, J., Wu, Z., Wang, F., 1993. Comments on ship domains. J. Navig. 46, 422–436.
Zhu, X., Xu, H., Liu, J., 2001. Domain and its model based on neural networks. J. Navig. 54, 97–103.